Measuring surface water salinity of Pearl River Estuary by MODIS 250-m imageries

Abstract

Aim: Moderate resolution imaging spectroradiometer (MODIS) 250-m imageries were used to evaluate the performance for developing the effective model of salinity using field spectra, the absorption coefficient of color dissolved organic matter (a<sub>cdom</sub>) collected on October 21 and November 2, 2012 in the Pearl River Estuary (PRE), China.

Methodology: Remote sensing reflectance of the four simulated MODIS bands (R<sub>s</sub>(Bi)) with a<sub>cdom</sub>(λ) data were used for algorithms development, which include least squares regression of the single band, difference between bands, band ratios, sediment index and their varieties with a<sub>cdom</sub>(λ) based on the dataset of November 2, 2012 (N=18). Additionally, the model of salinity with a<sub>cdom</sub>(λ) data was also calibrated (N=18).

Results: Results illustrated the optimum performance of quadratic model of sediment index for estimation of a<sub>cdom</sub>(355) (R<sup>2</sup>= 0.67, N=18, P<0.001), and the reverse linear model of a<sub>cdom</sub>(λ) is of the best accuracy for CDOM estimation of salinity (R<sup>2</sup>=0.83, N=18, P<0.001). An effective method to estimate surface water salinity from simulated MODIS 250-m bands was calibrated and validated using the independent dataset of October 21, 2012 (RMSE = 1.95‰, MRE = 9.65%, N = 17) in the Lingding Bay of PRE. The preferred models were further applied to retrieve a<sub>cdom</sub>(355) and salinity data from the MODIS 250-m data in the coastal and inner Lingding Bay of PRE. The result presented rationality of salinity distribution of PRE. The MODIS 250-m salinity mapping was validated based on in-situ measurements, and presented a good salinity mapping accuracy (RMSE=1.72‰, MRE=8.24%, N=10). The study proved the robustness of these algorithms for a<sub>cdom</sub>(355) and salinity estimation in the coastal and inner Lingding Bay of PRE by MODIS remote sensing.

Interpretation: Therefore, the effective method can be applicable in detecting variability of CDOM concentration and salinity during tidal cycle in a high frequency (two times during daytime), which proves the detection ability of MODIS 250-m imageries in estuarine and coastal waters. It provides the water supply and conservancy authorities spatially and temporally understand the marine intrusion in the Lingding Bay of PRE.

Key words: Color dissolved organic matter, MODIS 250-m, Pearl River Estuary, Salinity
Introduction

Marine intrusion into rivers is seasonal and periodic hydrological event in the coastal estuary area, which usually occurs in the winter with few freshwater inflow. The dynamic forcing of marine intrusion is caused by the change of fresh water inflow, tidal amplitudes, wind speed and wind direction. In recent years, due to global change acceleration (sea levels rise, drought, population explosion, economic development and so on), marine intrusion in the Pearl River riverway appears earlier, lasts longer and involves more cities (Yin et al., 2006; Jamal et al., 2018). The invasion of sea water has brought a lot of harm: the increase in salinity in the freshwater affects industrial and agricultural water first, distribution of nutrients in water next, which changes the environment in estuarine ecosystem (D’Sa et al., 2000; Mao et al., 2004; Xiao and Liu, 2018). Common method for marine intrusion is measuring salinity of time series at a station, which need a large number of stations and long-term data for PRE. Common method cannot monitor spatial change during the marine intrusion and cannot meet the needs of the water supply and conservancy authorities in the PRE. Based on effective approaches for spatial and temporal salinity simulation, contributes to understand the principle and method of sea water intrusion into estuarine ecosystems.

Remote sensing data has the ability to provide synoptical view of water quality of the entire coastal region of interest. More over new age satellite sensors have the ability to provide remote sensing picture of the earth surface in every 24 hours. Thus, continuous monitoring of surface water in costal environment is possible in a daily frequency. The theoretical basis for studying the salinity of water bodies by means of remote sensing, is the inverse correlations found between color dissolved organic matter (yellow substance) and salinity in coastal seas (Jerlov, 1968; Mckee et al., 1999). Because of the distinct optical signal of CDOM in the visible spectrum (Bricaud et al., 1981; Bricaud et al., 2012; Doerffer and Schiller, 2007; Lee et al., 2010; Tilstone et al., 2012; Werdell et al., 2013; Abbas et al., 2018). Therefore, it is feasible to interpret remote sensing ocean color in terms of salinity, from an aircraft or satellite.

Some researchers demonstrated that the multispectral images to be transmitted from this multispectral scanner would be useful in the identification and delineation of the runoff-influenced waters found along the west coast of Ireland (Monahan and Pybus, 1978). Some researchers found an opposite relationship between CDOM and salinity and defined the relationships in the Clyde Sea (Bowers et al., 2000; Chuanlei et al., 2018). Other researchers got the satisfactory estimation of CDOM and salinity in the Clyde Sea from remote sensing ocean color based on two key optical characteristics in some regions of freshwater inflow. First, CDOM has the strong effect on ocean color with relatively high concentrations. Next, the significant relationship exists between salinity and CDOM originating from fresh water inflow (Binding and Bowers, 2003).

Recent work in coastal ocean waters indicates the band-ratio algorithms of water reflectance can be applied to recover the absorption coefficient of CDOM (D’Sa and Miller, 2003; D’Sa et al., 2006; Castillo and Miller, 2007; Johannessen et al., 2003; Mannino et al., 2008; Naik et al., 2011; Shanmugam, 2011; Mannino et al., 2014; Razzak et al., 2018). Several studies of optical and fluorescent characteristics of CDOM and salinity have been also reported in the PRE (Chen et al., 2003; Chen et al., 2004; Hong et al., 2005; Fang et al., 2010; Fang et al., 2009). Chen et al. (2003) simulated distribution of yellow substance using Sea-viewing Wide Field-of-view Sensor (SeaWiFS) in the Lingding Bay of PRE (Chen et al., 2003; Kibria et al., 2018).

Fang et al. (2009, 2010) validated the models between total suspended solids and spectra of surface water in different salinity ranges and developed the methods to monitor salinity distribution of surface waters from Earth Observing-1 Advanced Land Imager and Hyperion satellite imageries in the PRE (Fang et al., 2010; Fang et al., 2009). However, based on remote sensing technology, the salinity simulation of the Pearl River estuary is still limited by the factors such as the satellite operating cycle and weather factors, in addition, the sensors with low spatial resolution are not capable of detecting marine intrusion. The existing models of salinity prediction from remote sensing imageries cannot meet the needs of marine intrusion management in the PRE.

The MODIS 250-m data is particularly suitable for ocean color remote sensing thanks to its twice daily coverage and appropriate spatial resolutions for sediment migration. Some recent models have been developed for retrieving CDOM in the optically complex estuarine water based on MODIS. A group scientist found that field remote sensing reflectance values were significantly correlated to CDOM, and successfully derived CDOM absorption from a MODIS band-ratio algorithm in NW Florida estuaries (Schaeffer et al., 2015). Others group researcher detected the slope change of linear relationship between CDOM and salinity with position (salinity range: 24%-32%) within the Bay (Hu et al., 2004). Some researchers developed and validated ocean color satellite algorithms for the estimation of \( \alpha_{\text{CDOM}} \) in the estuarine and continental shelf waters along the northeastern U.S. coast (Mannino et al., 2008). However, there are not many research of MODIS-related algorithms for spatial mapping salinity field, especially in the PRE. Therefore, the objectives of our study are (1) to develop an algorithm using in-situ measurements and simulated MODIS bands from our study region, (2) examine the negative correlation between salinity and CDOM originating from fresh water inflow in the PRE, (3) validate these algorithms for 250-m spatial resolution MODIS data, and (4) estimate surface water salinity and map its rationality in the Lingding Bay of PRE.
Materials and Methods

Study area: The PRE is a partially mixed estuary and influenced by tidal current from the Pacific Ocean. Tides invade through the Luzon Strait with tidal range of 0.8-1.63 m (Ye and Preiffer, 1990). The Pearl River is famous in the world with annual runoff of 3.26×10⁶ m³. Suspended sediment load of Pearl River is about 7.11×10⁷ kg. Marine intrusion into rivers usually occurs in the dry season (November to January of next year) with small freshwater discharges in the PRE. The Pearl River Estuary is with well-developed river system and a lot of tributaries. The shape of Lingding Bay is an inverted funnel. The north side is relatively narrow and the south side is relatively wide. There are four outlets, located from the north to south of the Bay (Chen et al., 2005).

Data collection and processing: The field sampling time is from 9:30 to 14:30 on October 21 and November 2, 2012 (Fig. 1). In situ measurements and water sampling from 10 locations are synchronous with MODIS satellite imagine time. Salinity of surface water was measured on the spot using a portable meter (YSI® 30/30SET). Exact locations of sampling stations were measured by high precision global positioning system (RMSE < 10 m). Water samples were collected and stored in cooler polypropylene bottles and transported to the laboratory within 4 h. Water quality of each sample was analyzed in South China Sea Institute of Oceanology, Chinese Academy of Sciences. Collection, storage, and measurement of sample was carried out in line with the Technical Specifications Requirements of Surface Water of China.

The field spectral measurement of water was carried out with an ASD Field Spec spectroradiometer manufactured by Analytical Spectral Devices, Inc. The spectroradiometer works in the bands ranging from 350 to 2,500 nm at increments of 1.4 nm from 350 to 1,000 nm and 2 nm from 1,000 to 2,500 nm with a field view of 25°. The spectral resolution can be interpolated into 1nm by the specific tool of the spectroradiometer. To effectively reduce the shadow of the boat and the influence of solar radiation, observation azimuth angle of the spectroradiometer is 130° (zero degree of solar azimuth angle), and observation zenith angle is controlled between 30° and 45°. The adopt of an observation angle can eliminate influence of direct sunlight and avoid the interference of boat's shadow. In the spectral measurements of each station, radiance of surface water (L_w), standard gray board (L_g) and skylight (L_sw) were measured in order. Integral time of the spectroradiometer was 172 ms, and ten spectral records were continuously acquired for each target. The entire field measurements procedure was according to the Ocean Optical Protocols (Revision 3) by National Aeronautics and Space Administration (Muerller and Fargion, 2002).

Generally, reflectance of remote sensing (Rrs) of water is calculated by ratio of water-leaving radiation and total incident radiant flux of surface water (equation (1)).

\[
Rrs = \frac{L_w(\lambda)}{E_d(\lambda, 0°)}
\]  

(1)

where \(L_w(\lambda)\) refers to water-leaving radiation (\(\lambda\) stands for wavelength), \(E_d(\lambda, 0°)\) refers to total incident radiant flux of surface water.

\(L_w(\lambda)\) refers to spectral information of water, which is reflected by the water–air interface, and \(L_w(\lambda)\) can be calculated by equation 2.

\[
L_w(\lambda) = L_{sw}(\lambda) - rL_{sky}(\lambda)
\]

(2)

where \(L_{sw}(\lambda)\) is total radiation of surface water, \(L_{sky}\) is from the diffused radiance of the sky, and \(r\) is reflectance of the skylight from the water–air interface (Mobley, 1999).

The value of \(r\) is decided by the solar azimuth, the roughness of surface water and wind speed, and so on. The wind speed was not more than 4 m s⁻¹ during field sampling, thus, the
The value of $r$ was set as 0.021 (Tang et al., 2004).

$$E_r(\lambda, \theta') = \frac{nL_\lambda(\lambda)}{P_r(\lambda)}$$

where $L_\lambda(\lambda)$ is the radiance of standard 30% gray board and $P_r(\lambda)$ is the reflectance of the gray board.

Samples of surface water were analyzed in the laboratory within 24 hr after field sampling. The absorption coefficient of CDOM was measured and calculated by the advanced Gelbstoff Optical Analysis Laboratory System.

The set from two different days containing 35 water samples, which were analyzed in the study (Table 2). 17 samples were picked from PRE-on October 21, 2012. The salinity ranges from 14.18‰ to 18.66‰, and the corresponding average value is 16.35‰. 18 water samples were collected from PRE-on November 2, 2012. The salinity ranges from 12.59‰ to 20.11‰, and the corresponding average value is 15.68‰. CDOM absorption coefficient at 355nm, the range of $a_{CDOM}(355)$ is from 0.6276 m$^{-1}$ to 1.2354 m$^{-1}$. CDOM absorption coefficient at 400nm, the range of $a_{CDOM}(400)$ is from 0.2755 m$^{-1}$ to 0.5970 m$^{-1}$. CDOM absorption coefficient at 440nm, $a_{CDOM}(440)$ ranges from 0.1516 m$^{-1}$ to 0.3725 m$^{-1}$.

Table 1: Date and location of field measurement and sampling in the studied area

<table>
<thead>
<tr>
<th>Data</th>
<th>Location</th>
<th>Samples</th>
<th>Model calibration</th>
<th>Model validation</th>
<th>MODIS imageries validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>21/10/2012</td>
<td>Lingding Bay</td>
<td>17</td>
<td>0</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>2/11/2012</td>
<td>Lingding Bay</td>
<td>18</td>
<td>18</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>In total</td>
<td></td>
<td>35</td>
<td>18</td>
<td>17</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2: Statistics characteristic of the absorption coefficient of CDOM and salinity collected from the Pearl River Estuary

<table>
<thead>
<tr>
<th></th>
<th>Maximum</th>
<th>Minimum</th>
<th>Mean</th>
<th>StdDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>26.9</td>
<td>22.0</td>
<td>25.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Salinity (‰)</td>
<td>20.11</td>
<td>12.59</td>
<td>16.03</td>
<td>1.94</td>
</tr>
<tr>
<td>Transparency (m)</td>
<td>1.2</td>
<td>0.4</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>$a_{CDOM}(355)$ (m$^{-1}$)</td>
<td>0.3725</td>
<td>0.1516</td>
<td>0.2562</td>
<td>0.0499</td>
</tr>
<tr>
<td>$a_{CDOM}(400)$ (m$^{-1}$)</td>
<td>0.5970</td>
<td>0.2755</td>
<td>0.4473</td>
<td>0.0796</td>
</tr>
<tr>
<td>$a_{CDOM}(355)$ (m$^{-1}$)</td>
<td>1.2354</td>
<td>0.6276</td>
<td>0.9926</td>
<td>0.1799</td>
</tr>
</tbody>
</table>

Reflectance data and processing: To analyze the spectral characteristic of different stations, some spectral reflectance was selected and presented in Fig. 2. There was a peak near 575 nm in spectral variation of $R_s$ for all spectral curves. Then, it was a rapid drop in the blue band because of the strong absorption by particulate matter and dissolved materials. In general, within MODIS 250-m spectral $R_s(B1)$ (614–682 nm) the light backscattering from suspended substance mainly work for the reflectance of surface water, as a result of powerful absorption by pure water and CDOM (Petus et al., 2010). However, all spectral curve presented an accelerated decline from 650 nm, especially near the band of 657 nm, which is central wavelength of first band of MODIS 250-m. Previous studies showed particle scattering would decrease when increasing particle sizes due to decreasing particle scattering efficiency, and the increase of particle sizes was owing to the increase of organic matter (Binding et al., 2009). It illustrates that the change of CDOM can be explained by $R_s(B1)$ in the study area. Within MODIS 250-m spectral $R_s(B2)$ (820-902 nm), lower spectral values in $R_s(B2)$ than $R_s(B1)$ are due to the strong absorption by pure water (Hale and Querry, 1973; Pope and Fry, 1997; Smith and Baker, 1981). The relationship between the magnitude of the reflectance spectra and the change of CDOM absorption coefficient is Complex and implicit. Thus, it is difficult to retrieve CDOM absorption coefficient using the common single bands models.

To evaluate the performance of MODIS imagery for marine intrusion in the PRE, the 18 in situ reflectance ($R_s(i)$) on November 2, 2012, were transformed to MODIS 250-m reflectance data according to MODIS 250-m response functions.
using Eq. (4):

\[ Rrs(Bi) = \frac{\sum_{i=1}^{n} S(\lambda_i) \cdot Rrs(\lambda_i)}{\sum_{i=1}^{n} S(\lambda_i)} \]  \tag{4}

where, \( \lambda_i \) and \( \lambda_n \) are minimum and maximum of the corresponding band \( i \) of MODIS (\( i = 1, 2, 3 \) and 4). \( S(\lambda) \) is the spectral response function of MODIS 250-m image. Thus, the four \( Rrs \) data (\( Rrs(B1) \), \( Rrs(B2) \), \( Rrs(B3) \) and \( Rrs(B4) \)), corresponding to the four MODIS 250-m band values, were simulated in each sampling station.

**Satellite data and processing:** MODIS is an important spectroradiometer on the Terra and Aqua satellites. Terra satellite was successfully launched on December 18, 1999, and it passes south to north over the equator at about half past ten in the morning. Aqua satellite was launched on May 4, 2002, and it passes from south to north across the equator at about 13:30 h. MODIS Terra and Aqua are recording images of global surface every one to two days, acquiring important spectral data of different wavelengths (URL: http://modis.gsfc.nasa.gov/). Wavelengths of these data range from 0.4 \( \mu \)m to 14.4 \( \mu \)m and is divided into 36 bands. These data can be used for monitoring of the land, ocean, and atmosphere of troposphere. Two bands in 36 bands (band1 and band2) are recorded at image resolution of 250 m, with five following bands (band3-band7) at 500 m.

MOD09GQ and MYD09GQ provide Bands 1 and 2 at a 250-meter spatial resolution, surface reflectance of Bands 1 and 2 are provided by Science Data Sets. The center wavelength of band 1 is at 645 nm and band 2 at 859 nm. MOD09GA and MYD09GA are the reflectance products of global surface. Their spatial resolution is 500 m including bands 3 and 4 centered at 555 and 469 nm. These data were employed to estimate the absorption coefficient of CDOM and salinity using the models in the work.

MODIS 09 products were selected across the PRE on October 21 and November 2, 2012. Because of the high cloud cover (average cover of 70%) on 2 November 2012 for Aqua data, less or free cloud images from 21 October 2012 and 2 November 2012 aboard on Terra, 21 October 2012 aboard on Aqua, were selected to evaluate the performance of marine intrusion models in the PRE.

The geometric correction is one of the most important step in MODIS preprocessing, which was carried out by the MODIS Reprojection Tool. In order to facilitate visualization and analysis, First, image contrast was enhanced by the software (Environment for Visualizing Images, version 4.6). Second, 250-m spatial resolution data at 555- and 469-nm can be generated by interpolating of the 500-m resolution data based on an image sharpening tool. Then, MODIS 250-m Red-Green-Blue images were composed by the 645-, 555-, and 469-nm bands data.
Fig. 3: Comparison of regression models of CDOM absorption coefficient (m⁻¹) in the form of single band, sediment index and band ratio (N = 18, 0.6276-1.2354 m⁻¹).
Bowers et al. (2000) theoretically proved a linear relationship between the CDOM absorption coefficient and band ratio of red light to other color, when the contribution of suspended substance is weaker than that of CDOM on the optical signature (Bowers et al., 2000), and the magnitude of $a_{\text{CDOM}}(\lambda)$ relates to its source and composition, which is different in the different waters (Mannino et al., 2014). Thus, the Fig. 3 (C) demonstrated that the optical signature of CDOM was stronger during the field measurements in the PRE, which showed the estuarine environment was affected by artificial particles and dissolved matter (Xia et al., 2004).

**Relationship between $a_{\text{CDOM}}(355)$ and salinity:** The correlation between $a_{\text{CDOM}}(355)$ and salinity was analyzed from field data on November 2, 2012 (table 3). There is significant correlation between $a_{\text{CDOM}}(355)$ and salinity as shown in the Fig. 4. $a_{\text{CDOM}}(355)$ increases linearly with the decreasing salinity. Equation (6) describes the correlation including 18 sample data with a good linear correlation ($R^2 = 0.83$).

$$\text{Salinity} = -12.721 \times a_{\text{CDOM}}(355) + 28.392 \quad (R^2 = 0.83, N = 18, P<0.001) \quad (6)$$

where $a_{\text{CDOM}}(355)$ is the CDOM absorption coefficient at 355nm.

Usually, a linear correlation between $a_{\text{CDOM}}(355)$ and salinity in estuary, indicates that CDOM is from upstream freshwater (Hong et al., 2005). With rapid economy development and population increase in the Pearl River Drainage Area, dissolve organic matter and organic suspended matter accumulate in the river. Therefore, CDOM was rooted from upstream and the nearby cities and villages in the PRE. However, the reverse linear correlation between $a_{\text{CDOM}}(355)$ and salinity is regional, and its slope depends on the CDOM concentration where the salinity is zero (Binding and Bowers, 2003). With types of organic matter, number and duration of rainfall, change in the size of the basin, the slope will undoubtedly vary with geography and time.

This relationship is comparable to those obtained by the previous studies in the Clyde Sea (Mckee et al., 1999; Bowers et al., 2000) and in the PRE with the smaller slope of the regression
Validation of the models for $a_{\text{CDOM}}(355)$ and salinity: To verify the performance of the MODIS 250-m models, the determination coefficients ($R^2$), the mean relative error (MRE) and the root mean square error of salinity estimation (RMSE) were used for evaluation accuracy of the calibrated models. The best-fitting model for detecting marine intrusion was determined by comparison of the $R^2$, RMSE and MRE.

Salinity is used as the sole evaluation index for the models, because the CDOM absorption coefficient of water samples wasn’t measured on October 21, 2012 (Table 4). The field measured data was processed in the following way. First, the field measured data was processed in the following way. First, the

Table 4: Salinity of samples on October 21, 2012 in the Lingding Bay of PRE.

<table>
<thead>
<tr>
<th>Station#</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salinity (%o)</td>
<td>14.18</td>
<td>15.35</td>
<td>14.76</td>
<td>17.33</td>
<td>17.26</td>
<td>18.66</td>
<td>18.61</td>
<td>17.85</td>
<td>17.85</td>
<td>17.99</td>
<td>16.37</td>
<td>16.35</td>
<td>15.83</td>
<td>15.78</td>
<td>15.67</td>
<td>15.98</td>
<td>16.45</td>
</tr>
</tbody>
</table>

![RMSE = 3.81‰, MRE = 20.39%](image1)

![RMSE = 3.96‰, MRE = 21.08%](image2)

![RMSE = 2.09‰, MRE = 9.83%](image3)

![RMSE = 1.95‰, MRE = 9.65%](image4)

Fig. 5: Scatter plots of measured vs. estimated salinity for the four models: A, the linear model of $R_{(B2)}/R_{(B1)}$; B, the linear model of sediment index; C, the quadratic models of $R_{(B2)}/R_{(B1)}$; D, the quadratic models of sediment index. The RMSE and MRE of every model were calculated and presented in the figure using the independent dataset (the number of samples (N) is 17, and the salinity range is 14.18–18.66‰).
Fig. 6: Mapping of $a_{\text{cord}}(355)$ using the quadratic model of sediment index from MOD09 and MYD09 imageries with 250-meter spatial resolution in the PRE, China.
reflectance of MODIS 250-m bands ($R_{(Bi)}$) were simulated from the 17 reflectance $R_{(l)}$ measured on October 21, 2012, using the band response function. Second, the CDOM absorption coefficient at 355nm ($a_{CDOM}(355)$) was estimated based on the four models (Fig. 3(C–F)) in each sampling station. Finally, the corresponding salinity of each station was predicted using Eq.6. Based on another 17 samples, the validation of the calibrated models (Fig. 3(C–F)) are carried out as shown in Fig. 5(A–D).

![Fig. 7: Mapping of salinity based on the reverse linear model of $a_{CDOM}(355)$ from MOD09 and MYD09 imageries with 250-meter spatial resolution in the PRE, China.](image)
remote sensing images for validating, and respectively. The models were applied to the MODIS 250-m the optimal models for estimation of model of the absorption coefficients of CDOM, are considered as the quadratic model of MODIS 250-m sediment index and linear estimated furtherly based on the linear correlation between (355) and salinity. The MREs for the quadratic model have got the least RMSE and MRE values based on the range for the linear model of sediment index is 21.08%, with RMSE = 3.96% (Fig. 5(B)). The salinity estimations calculated by the quadratic models of band ratio and sediment index were with RMSE = 3.81% (Fig. 5(A)). The MRE of the whole salinity with a mean value of 19.36‰. The lowest salinity was on the east under 16‰ were frequently found. Low salinity near Qiao island was probably side of Qiao island where the salinity values under 16‰ were were shown in Fig. 7. Although opposite variation tendency of salinity distribution existed, the salinity values are lower in the Lingding Bay than outside region, and in the river outlet than outside of outlet. There is the significant off-outlet increase of salinity from Fig. 7. The CDOM is more widely distributed in the Fig. 6(A) during the high tide, however the CDOM is concentrated in the outlets in the Fig.5(B) during the low tide. Some researchers demonstrate that the tide makes the turbidity of water higher (He et al., 2013; Li et al., 2003), and stronger interactions of runoff and tidal flow. Fig.8 show that the synchronization change of transparency and tidal elevation of water measured from 9:30 to 14:30 on November 2, 2012 in the PRE. Transparency of sampling water increases with tidal elevation increasing, vice versa. The dynamic changes of CDOM indicate that tidal elevation is key factor for it as the runoff and wind speed did not change (Gao et al., 2017; Wang et al., 2018; Fletemeyer et al., 2018). Additionally, the minor CDOM changes in Fig.6 also indicates microtidal variation with average tidal ranging from 0.8 to 1.63 m in the PRE (Fang et al., 2010).

The salinity values were estimated based on the reverse linear correlation between $a_{\text{CDOM}}$(355) and salinity. The results were shown in Fig. 7. Although opposite variation tendency of salinity distribution existed, the salinity values are lower in the Lingding Bay than outside region, and in the river outlet than outside of outlet. There is the significant off-outlet increase of salinity from Fig. 7. Fig. 7(B) presents an obvious boundary line of seawater and freshwater, which indicates weak interactions of runoff and tidal flow. According to tidal elevation data of October 21, 2012, Fig. 7(A) was imaged at around 10:40 h, when Lingding Bay is in the high tide, and Fig. 7(B) was imaged at around 13:50 h, when Lingding Bay is in the low tide. So, the distribution of salinity is more uniform in Fig. 7(A) than Fig. 7(B) due to tidal effect. Compared with the result on October 21, 2012, the salinity values are much higher (Fig. 7(C) on November 2, 2012. In Fig. 7(C), salinity show a large variation ranging from 15.41‰ to 27.45‰ with a mean value of 19.36‰. The lowest salinity was on the east side of Qiao island where the salinity values under 16‰ were frequently found. Low salinity near Qiao island was probably caused by injection of a lot of runoff from Humen, JiaoMen, HongQiMen and HengMen outlets. The low salinity areas were

The quadratic model of sediment index explained 66.9% of the absorption coefficient of CDOM variation, including 18 stations is underestimated. The MRE of the whole salinity range (14.18–18.66‰) for the linear models of band ratio is 20.39%, with RMSE = 3.81% (Fig. 5(A)). The MRE of the whole salinity range for the linear model of sediment index is 21.08%, with RMSE = 3.96% (Fig. 5(B)). The salinity estimations calculated by the quadratic models of band ratio and sediment index were closer to the measured values. The MREs for the quadratic model of band ratio and sediment index are 9.83% and 9.65%, and the RMSEs are 2.09% and 1.95‰, respectively.

The quadratic model of sediment index explained 66.9% of the absorption coefficient of CDOM variation, including 18 water samples for model calibration. Moreover, this quadratic model has got the least RMSE and MRE values based on the independent validation dataset (Fig. 5(D), N = 17, RMSE = 1.95‰, MRE = 9.65‰) as shown in Fig. 3(C-F). Thus, the quadratic model of MODIS 250-m sediment index ($(R_9(B1) - R_9(B2)) / (R_9(B1) + R_9(B2))$) is the optimal for monitoring of the CDOM absorption coefficient. Thus, the salinity values can be estimated furtherly based on the linear correlation between $a_{\text{CDOM}}$(355) and salinity.

Mapping $a_{\text{CDOM}}$(355) and salinity using optimal models from MODIS imagery: According the results above (Figs. 3, 4 and 5), the quadratic model of MODIS 250-m sediment index and linear model of the absorption coefficients of CDOM, are considered as the optimal models for estimation of $a_{\text{CDOM}}$(355) and salinity, respectively. The models were applied to the MODIS 250-m remote sensing images for validating, and $a_{\text{CDOM}}$(355) and salinity values of PRE were retrieved on October 21, 2012 and November 2, 2012. The mapping results of $a_{\text{CDOM}}$(355) were shown in Fig. 6. Fig. 6 presents the inversion result of the coastal and inner Lingding Bay water of PRE, however, the result of outer Lingding Bay of PRE is partially missing due to cloud cover. In general, the absorption coefficients of CDOM values are higher in the Lingding Bay than outside area, and west of Lingding Bay than east region. The apparent off-shore and out-off decrease of $a_{\text{CDOM}}$(355) means that the CDOM is brought by the Pearl River runoffs. In Fig.6, there is a great change in the $a_{\text{CDOM}}$(355) ranging from 0.07 m$^{-1}$ to 1.11 m$^{-1}$. The areas of higher absorption coefficients of CDOM were detected near Humen, Hengmen and Modaomen outlet where values are greater than 1 m$^{-1}$. The area of lower values is away from the estuary. From Fig. 6(A) and (B), the simulated images are from the MODIS images on the same day at different times and show the dynamic CDOM changes in the PRE. The CDOM is more widely distributed in the Fig. 6(A) during the high tide, however the CDOM is concentrated in the outlets in the Fig.6(B) during the low tide. Some researchers demonstrate that the tide makes the turbidity of water higher (He et al., 2013; Li et al., 2003), and stronger interactions of runoff and tidal flow. Fig.8 show that the synchronization change of transparency and tidal elevation of water measured from 9:30 to 14:30 on November 2, 2012 in the PRE. Transparency of sampling water increases with tidal elevation increasing, vice versa. The dynamic changes of CDOM indicate that tidal elevation is key factor for it as the runoff and wind speed did not change (Gao et al., 2017; Wang et al., 2018; Fletemeyer et al., 2018). Additionally, the minor CDOM changes in Fig.6 also indicates microtidal variation with average tidal ranging from 0.8 to 1.63 m in the PRE (Fang et al., 2010).

The salinity values were estimated based on the reverse linear correlation between $a_{\text{CDOM}}$(355) and salinity. The results were shown in Fig. 7. Although opposite variation tendency of salinity distribution existed, the salinity values are lower in the Lingding Bay than outside region, and in the river outlet than outside of outlet. There is the significant off-outlet increase of salinity from Fig. 7. Fig. 7(B) presents an obvious boundary line of seawater and freshwater, which indicates weak interactions of runoff and tidal flow. According to tidal elevation data of October 21, 2012, Fig. 7(A) was imaged at around 10:40 h, when Lingding Bay is in the high tide, and Fig. 7(B) was imaged at around 13:50 h, when Lingding Bay is in the low tide. So, the distribution of salinity is more uniform in Fig. 7(A) than Fig. 7(B) due to tidal effect. Compared with the result on October 21, 2012, the salinity values are much higher (Fig. 7(C) on November 2, 2012. In Fig. 7(C), salinity show a large variation ranging from 15.41‰ to 27.45‰ with a mean value of 19.36‰. The lowest salinity was on the east side of Qiao island where the salinity values under 16‰ were frequently found. Low salinity near Qiao island was probably caused by injection of a lot of runoff from Humen, JiaoMen, HongQiMen and HengMen outlets. The low salinity areas were

![Fig. 8: Transparency changes of water measured from 9:30 to 14:30 on November 2, 2012 in the PRE (Corresponding tidal elevation was presented by dash.](image-url)
also in the shoal with shallow water depth, according to the sea
graph of Lingding Bay. The salinity distribution of Lingding Bay is
subject to tide, runoff, wind and water depth, shows the dynamic
concentrations changes.

The MODIS 250-m salinity mapping was re-validated
using in-situ measured data (Table 5). Salinity data from 7 in-situ
samples on October 21, 2012 and 3 in situ samples on November
2, 2012 selected within an hour’s time difference between the
satellite transit and synchronous measurement. The comparison
graph of MODIS estimated salinity and in situ measured salinity
(Fig.9) showed the good relationship between the two ($R^2 = 0.87$).
The comparison also presented high precision of salinity
evaluation based on the two types of MODIS reflectance products
(RMSE = 1.72‰, MRE = 8.24%, and $N = 10$). Because of difficult
and complex conditions for in situ water sampling, the change
was little in optical characteristics of validation data set, with
dynamic range of salinity from 14.76‰ to 20.11‰. The validation
results present that the quadratic model of MODIS 250-m
sediment index and the reverse linear model of $a_{CDOM}(355)$ were
robust for estimation of $a_{CDOM}(355)$ and salinity, respectively in
the Lingding Bay of PRE (Jasinski, 2017; Cruz Campas et al., 2017;
Zhang et al., 2018).

This study developed the bio-optical models using field
data and simulated MODIS bands to search the best models for
salinity mapping from remote sensing in the Lingding Bay of PRE.
It was found that there is a linear relationship between the CDOM
absorption coefficient ($a_{CDOM}(355)$) and band ratio of red light to
other color based on data set on November 2, 2012, it
demonstrated that the optical signature of CDOM was stronger
compared to that of suspended particles in estuarine and coastal
environment (Bowers et al., 2000). Further, the quadratic models
of $R_a(B2)/R_a(B1)$ and $(R_a(B1) - R_a(B2)) / (R_a(B1) + R_a(B2))$
had the higher calibration accuracy among all models, explaining
more than 66% of the CDOM variation in the PRE. It was also
found that the $a_{CDOM}(355)$ is importantly related to salinity in the
PRE ($R^2 = 0.83$, $N = 18$, $P < 0.001$). Salinity decline linearly with
the raising of $a_{CDOM}(355)$, indicating that CDOM originated from
fresh water runoff in the Lingding Bay of PRE. The models were
validated by the independent data set on October 21, 2012.
The quadratic model of sediment index has got the least RMSE
and MRE values (RMSE = 1.95‰, MRE = 9.65%, $N = 17$), and was the
optimal model for simulation of the CDOM absorption coefficient
in the Lingding Bay of PRE.

The MODIS 250-m images on 21 October 2012 and 2
November 2012 aboard on Terra, 21 October 2012 aboard on
Aqua, were selected to evaluate the performance of optimal
salinity estimation models in the PRE. The result presented
rationality of salinity distribution. The salinity values are lower in
the Lingding Bay than outside region, and in the river outlet than
outside of outlet. The MODIS 250-m salinity mapping was re-
validated using in-situ measured data, which was collected within
an hour’s time difference between the satellite transit and synchronous
measurement (RMSE = 1.72‰, MRE = 8.24%, and
$N = 10$). The quadratic model of sediment index and the reverse
linear model of $a_{CDOM}(355)$ can be used for monitoring time-
variation in CDOM concentration and salinity respectively due to
tidal fluctuation, which proves the detection ability of MODIS 250-
m in estuarine and coastal waters in the Lingding Bay. Results
from this work demonstrated the rationale behind the sediment
index model and reverse linear model. Finding also revealed the
robustness of these algorithms for the absorption coefficient
of CDOM and salinity estimation based on in situ and MODIS 250-m
spectral data in the turbid estuary of PRE. Next, in situ datasets
with a wider salinity range and more sampling data would be used
for validation of MODIS 250-m salinity mapping, this can better
evaluate the accuracy and applicability of the salinity models by

Table 5: Comparison between MODIS derived and in situ measured salinity from seven in-situ samples on October 21, 2012 and three in situ samples on November 2, 2012.

<table>
<thead>
<tr>
<th>Station#</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Salinity (‰)</td>
<td>22.39</td>
<td>22.26</td>
<td>18.70</td>
<td>15.45</td>
<td>14.87</td>
<td>15.36</td>
<td>15.03</td>
<td>16.08</td>
<td>15.10</td>
<td>16.06</td>
</tr>
</tbody>
</table>

Fig. 9: Correlation between the measured and MODIS estimated salinity. Data at 10 stations collected synchronous with Terra MODIS and Aqua MODIS imageries were used for validation of salinity. The best linear fit is presented by dashed line.
remote sensing technology.

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